DOI: 10.13009/EUCASS2019-99

Estimation and measurement of base heating on Test Launch Vehicle

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Abstract

TLV (Test Launch Vehicle) is fabricated under the development plan of KSLV-II (Korea Space Launch Vehicle II) program. Comparing to flight data of a similar LV, it is predicted to have lower heating rate than KSLV-II. More detailed calculations are conducted by a CFD analysis and a radiative heat transfer analysis. Actual base heating rates are measured during the ground firing tests using the qualification model and the flight test using the flight model.

1. Introduction

1.1 Test Launch Vehicle

Republic of Korea's first LV (Launch Vehicle), KSLV-I (Korea Space Launch Vehicle-I) was developed based on the technical cooperation with Russia and launched in 2013. Next LV, KSLV-II (figure 1) was begin to be developed since 2010. It is a three-stage LV and its mission is to put a 1.5 ton satellite into 600 to 800 km of LEO (Low Earth Orbit) [1]. Four 75 ton liquid engines are clustered on the 1st stage of the KSLV-II, one 75 ton and one 7 ton engines are equipped on the 2nd and 3rd stage, respectively. In the 1st phase of the development plan from 2010 to 2015, Test facilities for engines and LV systems were constructed in the NARO space center (figure 2) where the launch complex is placed. Also, the first combustion test of the 75 ton engine was successfully conducted. In the 2nd phase of the plan from 2016 to 2018, the TLV (Test Launch Vehicle) was developed to verify the 75 ton engine and related system. The TLV is two-stage LV and designed based on the 2nd, 3rd stages of the KSLV-II.

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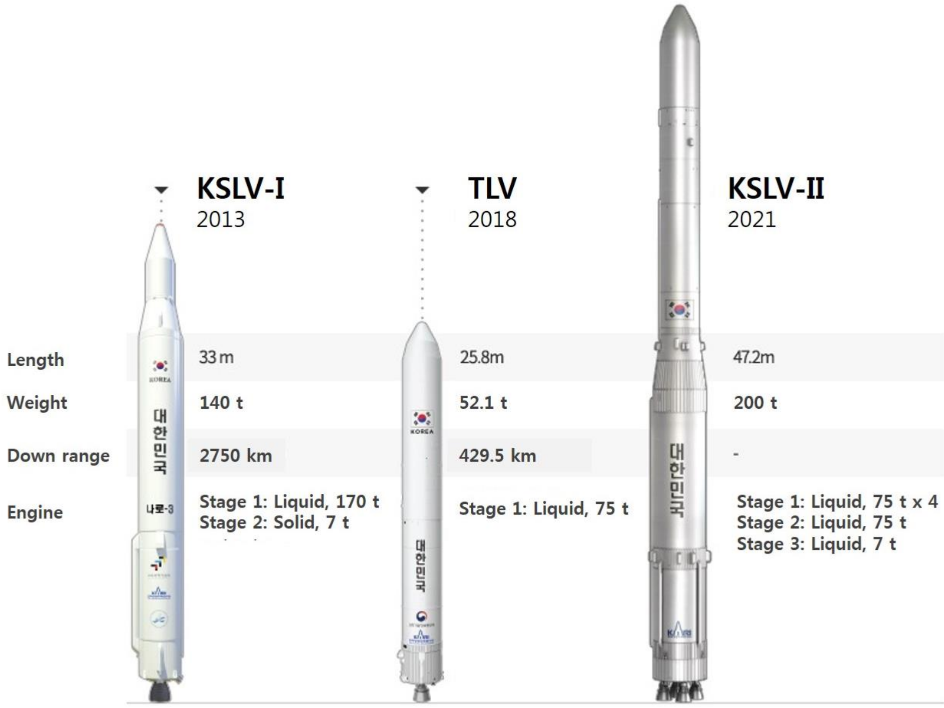

Figure 1 KSLV-I, TLV, and KSLV-II [2]

The 2nd stage of the TLV does not have its own function; it does not have an engine, pay-load, fairing, and does not conduct stage separation during the flight. The 1st stage is very close to the 2nd stage of the KSLV except the aft bay due to vertical holding on the launch pad (figure 3). An engine nozzle has also different shape due to different flight altitudes. Unlike the 2nd stage of the KSLV-II, the aft bay of the TLV is closed by a base plate.

Figure 2 Test stands in the NARO space center

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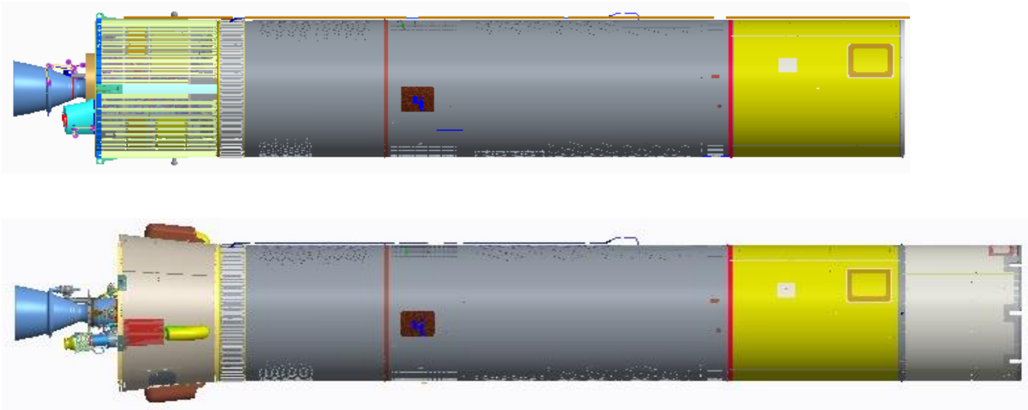

Figure 3 1st stage of the TLV (Up), and 2nd stage of the KSLV-II (Down)

1.2 Base heating

LVs are heated during the flight from high temperature engine exhaust plume and the base gets the most of the heat. Composition and number of engines, shape of the aft bay, flight altitude, and velocity majorly affects the base heating. In case of the KSLV-II which has four engines on the 1st stage, plume heat is transferred by thermal radiation in low altitudes and convective heat transfer is added in higher altitudes. Base heating of LVs with single engine like the TLV usually take place by thermal radiation and sometimes convective heat transfer occurs over 20 km of altitudes [3] and supersonic conditions [4].

2. Estimation of base heating

The TLV began to develop in earnest in the 2nd phase of KSLV-II development plan. Base heating rate is firstly estimated in several ways. Flight data of past LVs which are similar to the TLV are searched. Though specific combustion conditions of engines maybe different, THOR DSV-2A uses liquid propellant and has similar flight altitude as shown in the Table 1. The maximum base heating rate of THOR DSV-2A is 180 kW/m2 [5].

Table 1 Specification of the TLV and THOR DSV-2A [5]

	TLV	**THOR DSV-2A**
Flight Altitude	0~74 km (Altitude of MECO)	0~75 km
Engine composition	Single	Single
Thrust (vac.)	76.04 ton	76.06 ton
Isp (vac.)	298.5 sec	285 sec
Propellant	Kerosene / LOX	RJ-1(Liquid hydro-carbon) / LOX

Base heating rate of the TLV is also estimated by CFD calculation (figure 4) which is combined with the radiative transfer equation. Line by line method is used to calculate radiative properties and scattering by gas molecules is ignored. Conditions of 10, 15, and 20 km altitudes are considered for the calculation and the maximum base heating rate is around 20 kW/m2 at 10 km as the result. Base heating rates are decreased as the altitudes are increased (figure 5). Recirculation at the base is observed in every case but engine plume does not flow in reverse direction.

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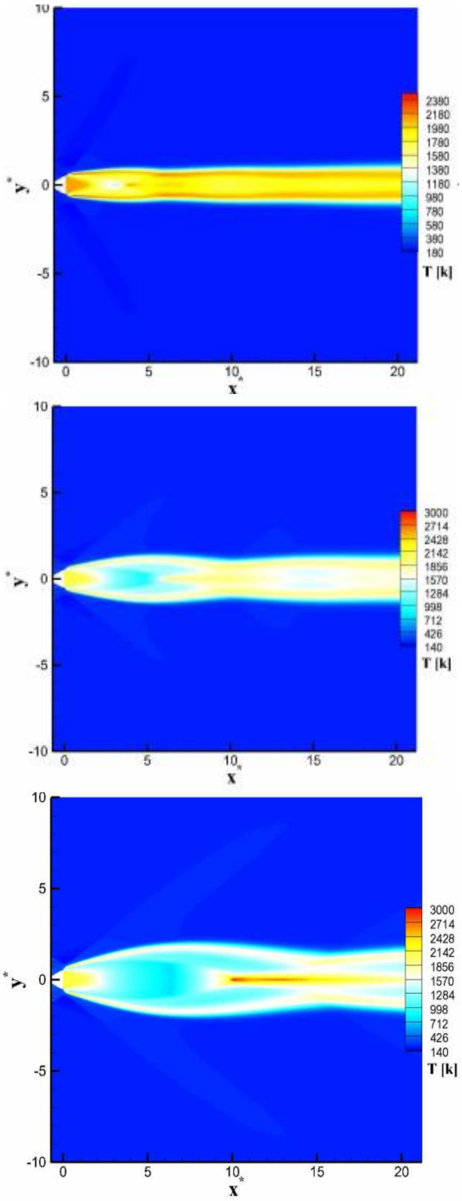

Figure 4 Calculated temperature of plume by CFD analyses (Up: 10km, middle: 15km, Down: 20km)

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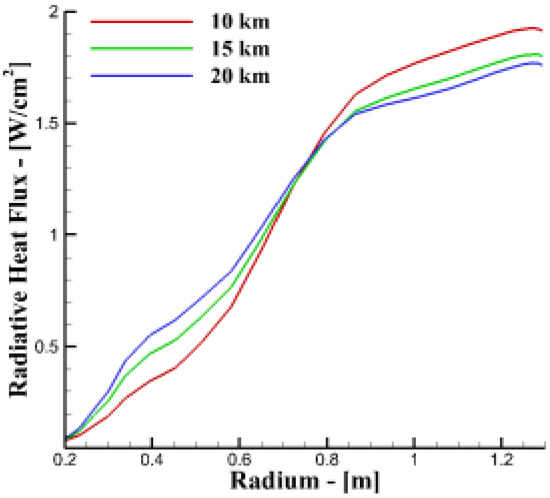

Figure 5 Calculated heat fluxes at the base by CFD analyses[6]

Another estimation is done using a commercial software, SINDA/FLUINT by enhancing the method introduced in reference 6. In the method, heat transfer from the plume is conducted by thermal radiation only, and the plume is assumed to have a conical shape with constant temperature distribution. The shape parameters, D2 and H in figure 6 are estimated by 1.44m, and 0.5m, respectively from the recorded video of the 75 ton engine firing test. The base plate is made of aluminum with 1.6 mm of thickness. The heat transfer by the engine nozzle is ignored. The calculated maximum heat flux from this method is around 50 kW/m2.

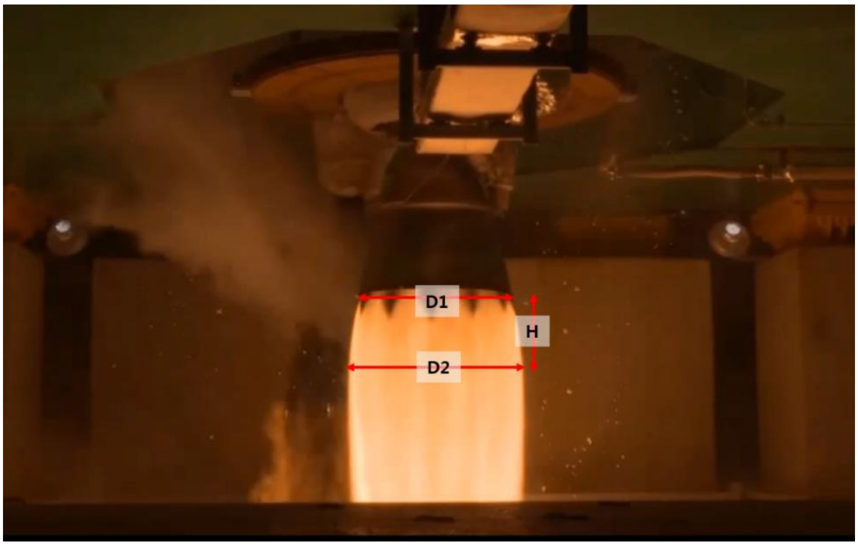

Figure 6 Recorded video of the 75 ton engine firing test

3. Thermal Protection System

3.1 Design

As shown in earlier, estimated base heating rates show large discrepancy according to estimation methods. The estimation suggests that the TPS (Thermal Protection System) is essentially needed to protect the base plate even though the base heating rate is around 20 kW/m2 which is the smallest estimation because the temperature of the base plate would be very high when the heat flux is applied. Also, the TPS of the KSLV-II can be used in the TLV because base heating rate of the KSLV-II is higher than that of the TLV when considering the largest estimation, 180

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kW/m2. Of course, applying the same TPS of the KSLV-II to the TLV is an excessive design and has unnecessary weight. However, in case of the TLV and its flight mission, the weight of the TPS is not a problem because it has enough weight margin. Therefore, the same design of the KSLV-II is applied to the TPS of the TLV (figure 7) for the sake of validating the manufacturing and integrating processes.
The TPS of the TLV consists of a rigid TPS and a flexible TPS. The rigid TPS made of an ablative material (Table 2) is attached on the external surface of the base plate.

Table 2 Material properties of the rigid TPS

Density	480 kg/m3
Tensile Strength	150 MPa
Thermal Conductivity	0.07 W/m-K
Specific Heat	2100 J/kg-K

The number of heat flux meters are three. They are located on the base plate with distances of 0.8m, 0.9m, and 1.1m from the center of the base. Though they have cooling pipes but are not cooled during the flight. A Pt100 type RTD sensor is attached on the inner surface of the base plate to measure the temperature.
Flexible TPSs are installed around the main engine nozzle and the exhaust duct of TP (Turbo Pump) which conduct TVC (Thrust Vectoring Control) motion during the flight. Its role is to block the plume heat flowing into the aft bay. Since it has to be 'flexible', it consists of several fireproof clothes.

Figure 7 Base plate with the rigid TPS of the TLV

3.2 Qualification tests

Rigid and flexible TPSs are qualified by specimen-level tests because they are usually degraded when heated. An environmental test consist of shaking-heating-shaking is conducted to qualify the mountability on the base plate and thermal protection performance. A test specimen is ablative material attached on the aluminum plate which has a size of 30 cm x 30 cm. In the shaking phases, specimen is mounted on the shaker and vibrated in horizontal and vertical directions (figure 8). Table 3 shows the test condition of the shaking phase. The test run time of the phase is 4 minutes.

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Table 3 Test condition of shaking phase

Freq. (Hz)	PSD	Tolerance
20 ~ 60	+3dB/oct	
60~ 1000	0.273g2/Hz	PSD: ±3dB
1000 ~ 2000	-6dB/oct	
overall	20grms	RMS: ±10%

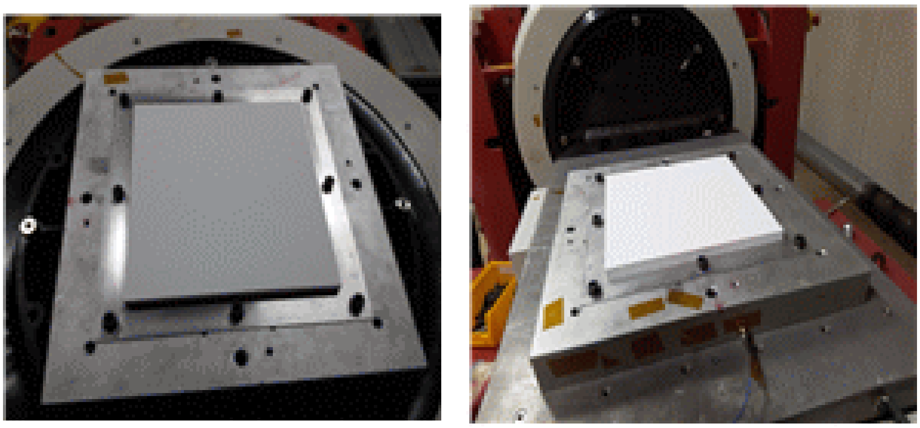

Figure 8 Test specimen mounted on the shaker (Left: vertical direction, Right: horizontal direction)

In a heating phase of the environmental test of the rigid TPS, the specimen is moved to the heating test apparatus and heated by thermal radiation. During the phase, the specimen is degraded by ablation and carbonization (figure 9). If it is still attached on the metal plate after the heating phase and its temperature stays in the normal range, it passes the phase. In the second shaking phase, the specimen is vibrated as done in the first shaking phase.

Figure 9 Before (Left), and after (Right) the heating phase

The flexible TPS is tested by a heating test to verify its thermal protection performance. A specimen of the flexible TPS is mounted in the heating test apparatus and heated. The temperature of inner surface is measured and if it stays in a normal range, it is passed. Repeated bending and unbending motion during the flight due to the TVC motion is also verified by an environmental test with mounting a special holder (figure 10) and specimen is bended, unbended with heating during the environmental test.

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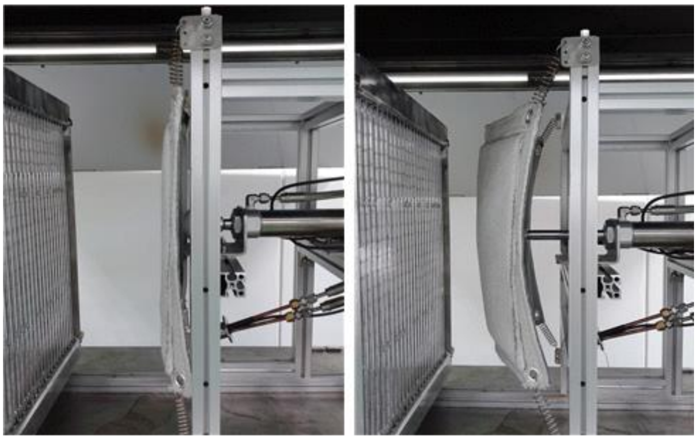

Figure 10 Environmental test of flexible TPS [7]

4. Measurement results

4.1 System level combustion tests

System level combustion tests are conducted using a qualification model of the TLV (figure 11). It is done at the PSTC (Propulsion System Test Complex) in the NARO Space center by three times. Engine operation times are 30, 60, and 151 sec., in the 1st, 2nd, and 3rd test. The maximum heating rate is below 50 kW/m2 in the first test, around 50 kW/m2 in the second and third test (figure 12).

Figure 11 Qualification model of TLV in the test stand for a combustion test

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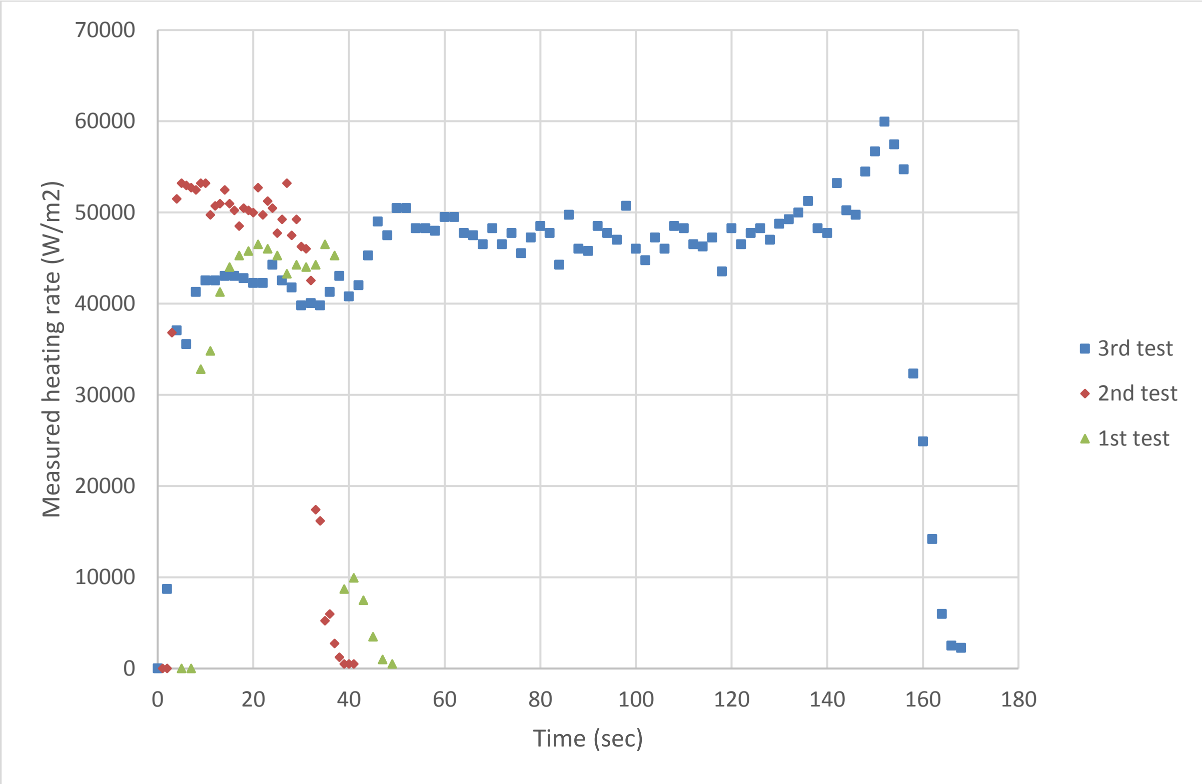

Figure 12 Measured heating rate in the combustion tests

At the end of the third test, flame is observed on a rigid TPS. After the test, it is observed that external surface of the rigid TPS and some part of the flexible TPS are burned (figure 13).

Figure 13 Rigid and flexible TPS after combustion tests

4.2 Flight tests

A flight test of the TLV is conducted in Nov. 2018 (figure 14). Engine operation stops 147.2 seconds after the lift-off, maximum altitude is 209.1 km.

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Figure 14 Flight test of the TLV

Measured radiative heat flux is around 40 kW/m2 in the early of the flight and is decreased as altitude is higher. Total heat flux is decreased firstly then begins to be increased until around 70 seconds and its maximum is about 65 kW/m2. Convective heat transfer which is not considered in the estimation may heavily affect to the result. After 70 seconds, total heat flux decreases and becomes virtually zero when the engine operation is ended.

5. Conclusion

The TLV is developed and launched to verify the 75 ton liquid engine and related system. Base heating rate of the TLV from engine exhaust plume is estimated in three ways; comparing flight data of similar LV, CFD analysis combined with radiative transfer equation, and radiation analysis using a commercial software. Estimated heating rates show large discrepancy from 20 kW/m2 to 180 kW/m2 according to the estimation methods. From the estimation, the same design of TPS with the KSLV-II is attached on the TLV. A rigid TPS and a flexible TPS are developed and qualified prior to the development of the TLV. In the system level static combustion tests, the maximum base heating rates are 45 – 50 kW/m2. In the flight test, it is measured around 40 kW/m2 but unexpected convective heat fluxes are observed in the middle of the flight.

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